SOME TESTS OF FLAT PLATE PHOTOVOLTAIC MODULE CELL TEMPERATURES IN SIMULATED FIELD CONDITIONS

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ABSTRACT

The nominal operating cell temperature (NOCT) of solar photovoltaic (PV) modules is an important characteristic. Typically, the power output of a PV module decreases 0.5% per °C rise in cell temperature. Several tests were run with artificial sun and wind to study the parametric dependencies of cell temperature on wind speed and direction and ambient temperature. It was found that the cell temperature is extremely sensitive to wind speed, moderately so to wind direction and rather insensitive to ambient temperature. Several suggestions are made to obtain data more typical of field conditions.

NOMENCLATURE

Module Position	Tilt angle measured from the module horizontal position about an axis through the center of the module parallel to the long axis. Azimuth angle based on south-facing module and wind direction. Winds of equal angle east or west of south are assumed to have identical effect. Example: 30° tilt, east wind: 30°/90°, 270°.
NOCT	Nominal operating cell temperature, measured at 100 mW/cm^2 irradiance, 20°C ambient, 1 m/s wind not east or west, open back and open-circuited, °C. (Note: current specifications in the U.S. use 80 mW/cm^2)
PV	Photovoltaic; refers here to silicon solar cell flat plate modules.
ΔT_{ca}	Difference in temperature between the cell in a module and the ambient air, °C.

INTRODUCTION

The nominal operating cell temperature (NOCT) of photovoltaic (PV) modules is an important characteristic. At the time this work was done, NOCT was defined as the cell temperature of a module irradiated at 100 mW/cm^2 (presently 80 mW/cm^2), 1 m/s wind velocity, not east or west wind, 20°C ambient temperature, and open circuited (1, 2). The power generated by silicon cell modules decreases by about 0.5% per degree Celsius rise in cell temperature (2); thus, at operating temperatures, modules produce about 15% less power than at room temperature. Accurate knowledge of the NOCT is important for rating modules, purchasing modules by power output, and in field application design.

Normally, the NOCT is measured out-of-doors in natural sunlight. An accurate determination of NOCT is difficult because of variations in the solar irradiance, ambient temperature, and wind direction and speed. Corrections for these variables must be applied to derive the NOCT (1, 2). Also, data taken within 30 minutes after an east or west wind, higher wind speeds or gusty conditions must be excluded. Data are useful only if taken during days with a light wind. However, 1-m/s winds are generally interspersed between a dead calm and somewhat higher speeds and with the wind direction variable.

To reduce some of the problems of measuring NOCT, an experiment was designed to (1) determine the NOCT of a typical flat plat PV module under controlled laboratory conditions, (2) study the parametric dependencies of cell temperature on wind speed and direction and ambient temperature, (3) compare results with similar measurements in the natural environment, (4) develop better correction factors for off-nominal conditions, and (5) evolve a better and alternate scheme to measure NOCT.

EQUIPMENT AND PROCEDURE

The experimental setup for the indoor cell temperature measurements is shown in Figs. 1-3. An artificial sun was provided by the 25-foot Space Simulator at the Jet Propulsion Laboratory in Pasadena, California. The maximum diameter of the solar beam with the optical system in use was 5.6 m. A 10-hp blower with a diffuser and a 2.3- × 1.7-m

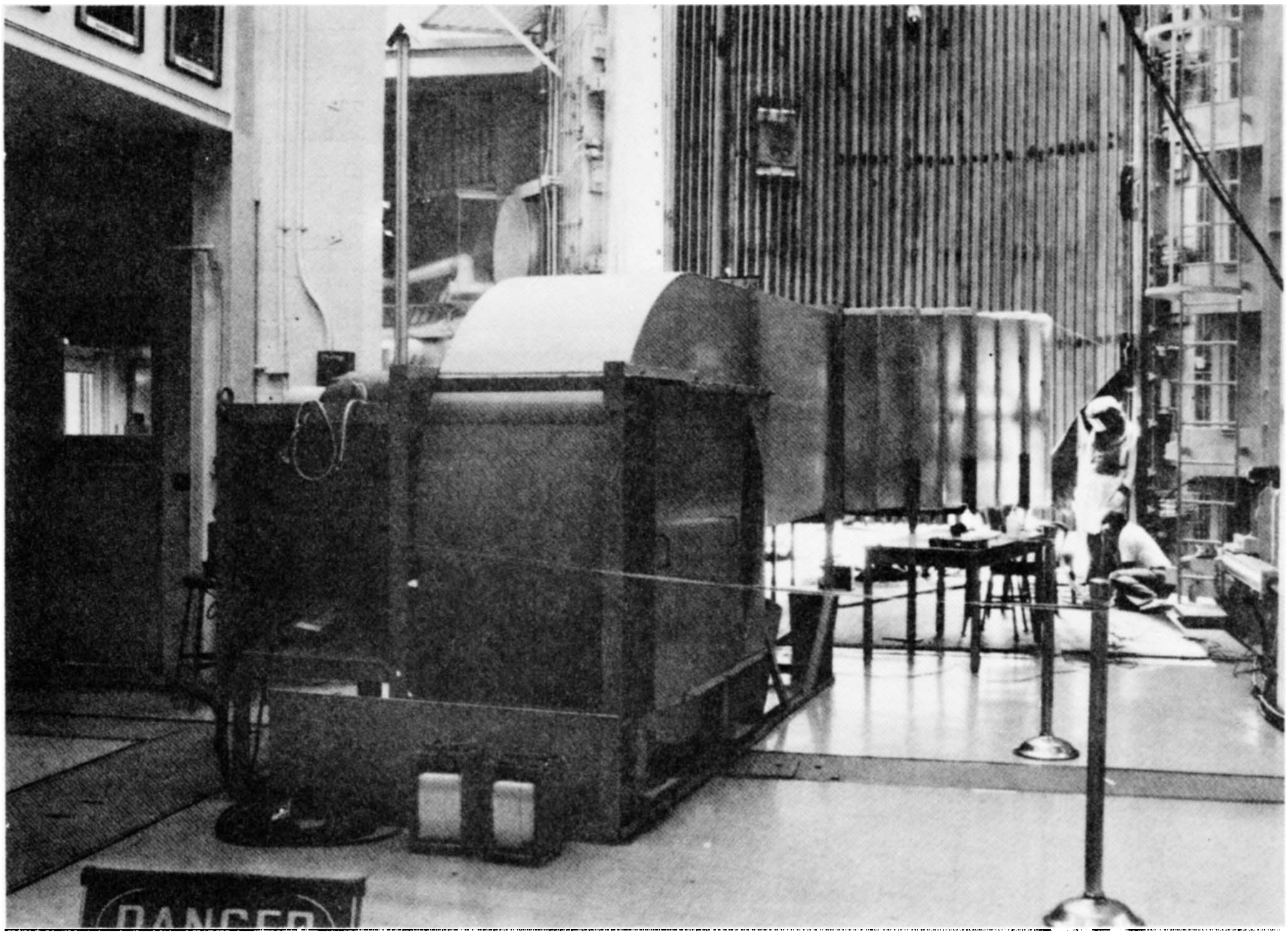

Fig. 1. Blower, duct, and space chamber used for NOCT measurements

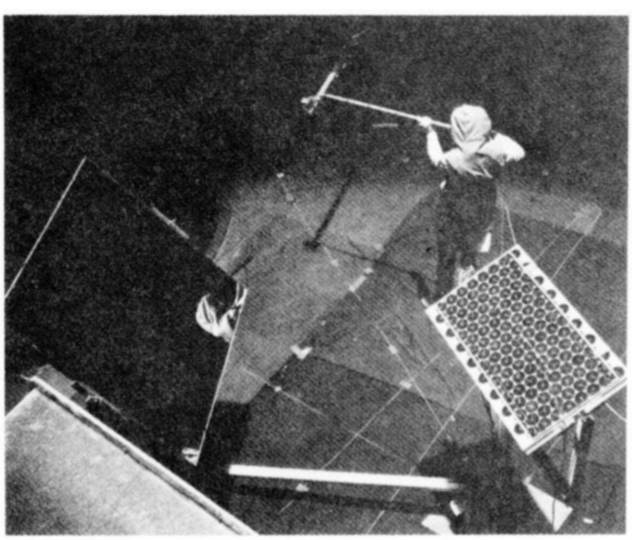

Fig. 2. Technician with "wand" at radiometer, calibration panel over module, and turning mirror

exit section provided free jet wind speeds varying from 0.5 to 3 m/s. The solar PV modules (up to 0.7 m wide × 1.2 m high) were mounted on a pedestal. They could be tilted from 0 to 45° solar incident angle and rotated 360°. The blower duct diffused the air from the blower to provide a uniform flow at the duct exit. Screens were used in the duct to provide uniformity. The ambient temperature was varied by turning building air conditioning and heat controls down or up. The blower merely recirculated building air. A turning mirror at the side rotated with the pedestal in the horizontal plane providing the makeup irradiance for the tilted module to maintain constant total irradiance with the vertically downward sun. The module rotation on its pedestal provided different wind directions. The angle convention used (Fig. 3) was for a south-facing module with winds possible from any angle. Thus, a south wind was 180°, east 90°, etc. In practice, only 180° rotation was used, south through east to north. By symmetry considerations, the wind angles of 180° - 270° - 360° were assumed equivalent to the 180° - 90° - 0° data, respectively. Thus, data taken at 30° tilt and 150° wind is represented as 30°/150°, 210°, since 150° and 210° are symmetrical about the N-S axis.

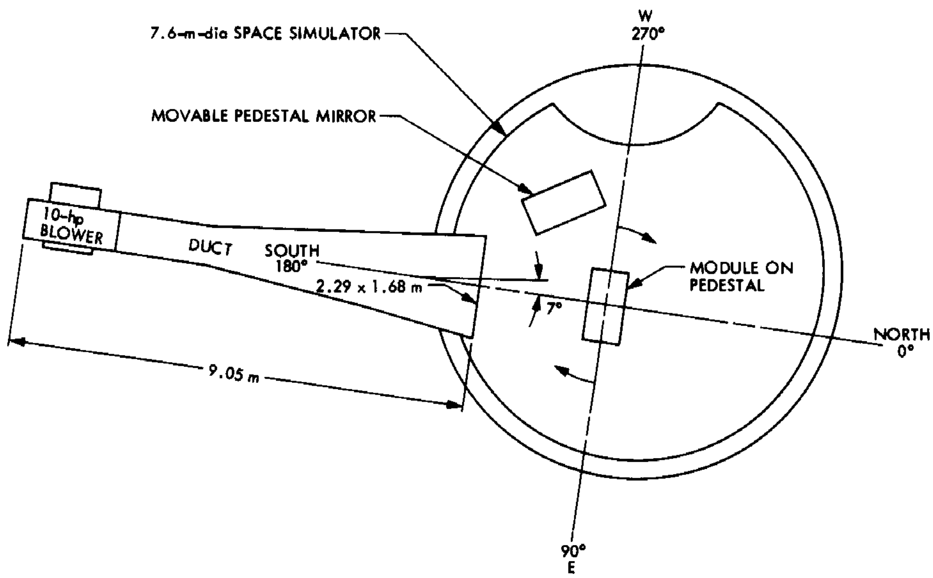

Fig. 3. Schematic of experimental setup

A calibration panel (Fig. 4) with 15 silicon cells from the same lot was fabricated to determine the irradiance variations on the module. For all of the tilt and wind variations, this panel was put on top of the module, and cell short-circuit scans of the calibration panel were taken to determine irradiances on the module (Fig. 2). The calibration panel was calibrated in a two-step process. First, the cells were tested in sunlight to measure their relative sensitivities. Then, during the test in the solar simulator, another cell was used to correlate the panel with a primary standard. This cell was mounted on a pole (the "wand") and put alongside a JPL Absolute Cavity Radiometer MK.4 located in the solar beam. By measuring the ratio of the radiometer/wand readings and then the wand/panel ratios (with the wand located at the panel), it was possible to determine the local irradiance at each solar cell location.

An Applied Solar Energy Corporation prototype module (ASEC 001) from JPL LSA Block IV stock was used for the primary cell temperature measurements (Figs. 2 and 5). Cell temperatures were measured to determine the effects of wind direction, wind speed, ambient temperature, and module tilt. Later, three other modules were tested at fixed conditions except for modest wind speed changes.

The modules and thermocouples used for this test were the same as those used previously for NOCT determination at the outdoor NOCT facility on top of Bldg. 248 at JPL. Thermocouple and solar cell panel data were printed out by a Kaye System 8000 thermocouple and millivolt recorder. Thermocouples were monitored on two cells for each module. The parameter of primary interest was ΔT_{ca}, the cell temperature minus ambient air temperature. For each module tilt, wind direction and speed setting, the cell temperatures were observed very carefully for stabilization. On the average, it took about 30 minutes for those two cell temperatures to stabilize to the criterion of ±0.1°C change per minute.

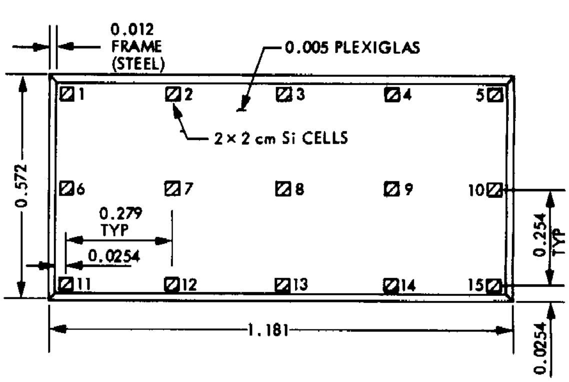

Fig. 4. Calibration panel (dimension in meters)

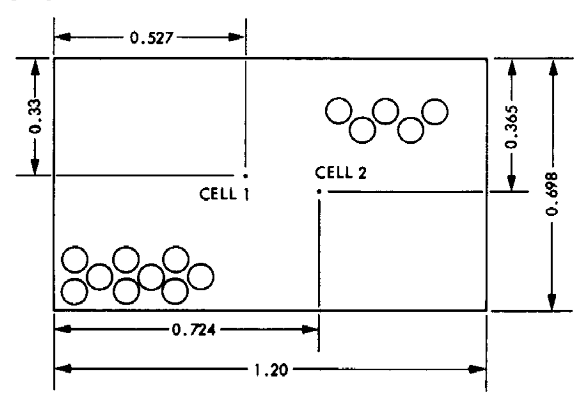

Fig. 5. Thermocouple location — ASEC module (view: sun side; dimensions in meters)

The accuracy of the temperature measurements was better than ±1°C. Calibrated thermocouples were used, and the same instrumented modules and thermocouples were used for both indoor and outdoor NOCT measurements. Wind uniformity was ±5% at the duct exit out to within a few centimeters of the edge. Uniformity was ±10% at the module pedestal location. The Series 6000-P Alnor Velometer used to measure wind speed was calibrated at the JPL low velocity Low Turbulence Wind Tunnel. The air jet cross section projected over the module provided 0.5 m excess on all sides in the worst condition (except at 45° tilt it was 0.4 m). Blower variations caused a ±2% change in air speed. Solar irradiance was accurate to ±3%. From instrumentation considerations only, absolute accuracy of the NOCT was probably better than ±4°C and relative accuracy between the various test conditions was about ±2°C.

The inaccuracies of the simulation in the chamber should be noted. Chamber solar irradiation was direct with essentially none of the diffuse sky component that is present in the natural environment. Of greater importance was the difference between the natural sky IR radiation and the radiation from the interior of the test chamber. Using a sky temperature of $T_{sky} = 0.914\ T_{air}$ and other appropriate values (1), an error in the radiation component of about 7 to 10% is possible. This would have the effect of increasing the NOCT by a degree or two above temperatures in the natural environment. Offsetting this somewhat was the smaller view angle of the hot floor in the test chamber. No attempt was made to simulate adjacent array modules. In a solar field most of the modules are shielded from the wind by adjacent modules. Limitations in size of the duct supplying the wind precluded using several modules in an array. Several other problems of chamber simulation are discussed in the next section.

RESULTS AND DISCUSSION

Table 1 contains the ΔT_{ca} (cell temperature minus ambient air temperature) measurements of the ASEC module. To account for irradiance variations from 100 mW/cm^2, the ΔT_{ca} was computed as

$$\Delta T_{ca} = \frac{(\text{Measured Temperature} - T\ \text{amb}) \times 100\ \text{mW/cm}^2}{\text{Interpolated Actual Irradiance}}$$

Reference 1 established theoretically and empirically the proportionality of ΔT_{ca} to irradiance.

Figure 6 shows the relationship between wind direction and ΔT_{ca} at several wind speeds and with ambient temperature at approximately 20°C. It is observed that the wind direction is very important and produces a maximum difference of 8°C in ΔT_{ca} at 1 m/s. Not only do the east or west winds cool the module efficiently, but those 30° on either side do also. (The high temperature measured at 60° and 2 m/s is believed to be an anomaly and will be discussed later.) The hottest conditions are with wind from due south and 30° off-south blowing on the tilted glass front of the module.

Table 1. Cell temperatures of ASEC 001 in simulated environment

Tilt/Wind Direction	Wind Speed, m/s	T_{amb}, °C	ΔT_{ca}, ($T_{cell} - T_{amb}$), °C		
			Cell 1	Cell 2	Mean
0/0,360	1.0	21.4	38.8	37.9	38.4
0/90,270	1.0	21.1	42.5	41.9	42.2
30/0,360	1.0	20.6	46.2	46.0	46.1
	2.0	21.1	33.6	33.3	33.4
30/30,330	1.0	20.5	44.8	45.7	45.2
	0.5	20.9	45.7	46.6	46.1
	1.0	21.0	43.3	45.2	44.2
	2.0	20.1	31.7	36.2	34.0
	0.5	35.4	44.7	45.5	45.1
	1.0	35.5	42.6	42.6	42.6
	2.0	35.3	31.7	33.0	32.3
	3.0	34.9	26.9	27.6	27.3
	1.0	20.7	44.1	45.2	44.6
	2.0	21.1	32.3	36.5	34.4
30/60,300	1.0	20.7	46.1	40.9	43.5
	2.0	21.1	39.6	35.6	37.6
30/90,270	1.0	20.7	42.2	41.1	41.7
	2.0	21.6	33.4	31.3	32.3
30/120,240	1.0	20.8	41.4	41.1	41.3
	2.0	20.0	31.6	31.5	31.6
	3.0	20.5	27.7	27.7	27.7
	1.0	34.8	39.1	39.2	39.1
	2.0	34.6	31.2	31.2	31.2
	3.0	34.6	27.6	28.0	27.8
30/150,210	1.0	21.2	49.1	49.7	49.4
	0.5	19.7	51.0	51.6	51.3
	1.0	19.2	48.6	49.6	49.1
	2.0	20.1	35.8	34.1	34.9
	3.0	19.7	32.8	32.1	32.4
	1.0	34.4	40.5	39.2	39.9
	2.0	33.3	35.9	33.2	34.5
	3.0	33.5	32.4	31.5	31.9
30/180	1.0	21.2	48.7	48.5	48.6
15/120,240	1.0	21.2	43.5	41.8	42.7
45/120,240	1.0	21.2	42.0	42.9	42.4

Figure 7 shows the effect of wind speed on ΔT_{ca}. In the 150°/210° wind direction case, there is as much as a 14°C drop in ΔT_{ca} for an increase of wind speed from 1 to 2 m/s. However, the high temperatures at 0.5 and 1.0 m/s, 150°, 210°, and T amb ≅ 20°C are believed to be nontypical of field conditions. A possible explanation for these high temperatures (and the anomalous high temperature mentioned in the last paragraph) may be deduced from the highly stable airflow conditions. It is suggested that stable eddies and/or shielding of the cooling airflow occasionally occurs at certain module areas. In most cases in the outside world, variations in wind speed and direction should smooth out local hot spots.

The data are believed to be accurate. The upper curve on Fig. 7 has a redundant data point at

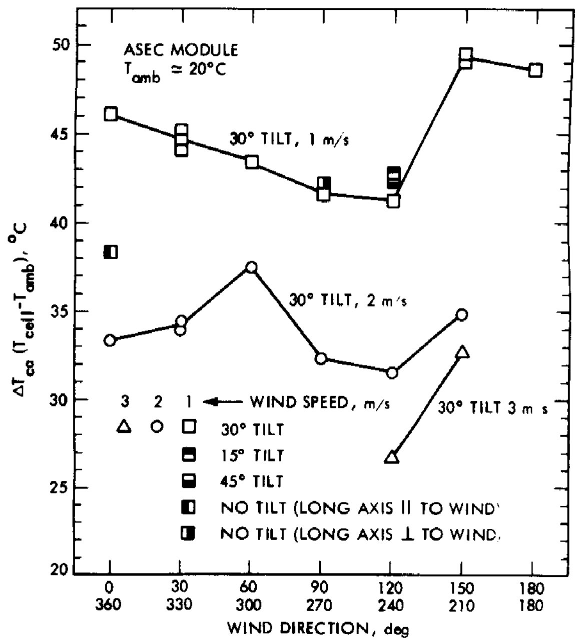

Fig. 6. Effect of wind direction on cell temperature rise

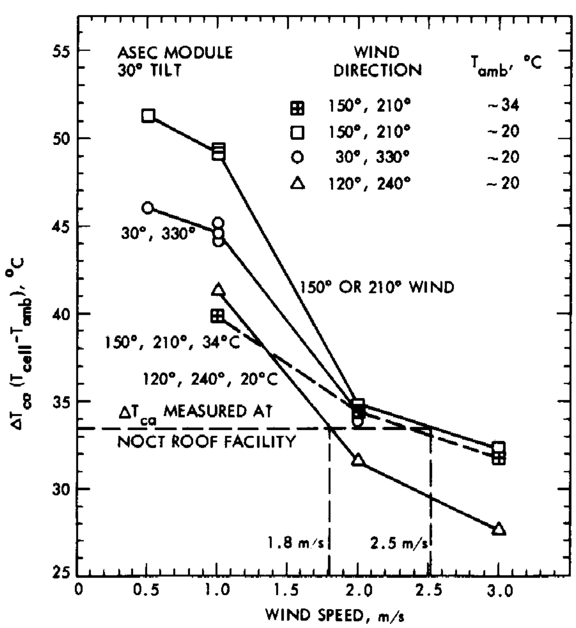

Fig. 7. Effect of wind speed on cell temperature rise

1.0 m/s and a higher ΔT_{ca} at 0.5 m/s. The dashed curve on Fig. 7 shows data in the same 30/150,210 configuration taken at T amb = 34°C. The ΔT_{ca} at 1 m/s has dropped a full 10°C, apparently because the change in ambient temperature was enough to alter the flow pattern and improve the cooling.

It is possible that there are other hot spots which affect the data. Even if so, on balance this should not raise the general level of cell temperature because for each hot spot there should be the equivalent in cold spots. The data are generally consistent except where noted, and hot spots are probably relatively rare. However, if this work is continued, the hot spot hypothesis should be checked by testing with more instrumented cells, making small changes in wind direction, etc.

More typical effects of a change in wind speed from 1 to 2 m/s are shown for wind directions 30,330 and 120,240 at 20°C. Here the drop in ΔT_{ca} is 9.5 to 10°C. The 34°C data for these positions is generally consistent with the 20°C data. Since convective heat transfer with laminar flow is proportional to the square root of the wind speed (3), a 12 or 13°C change is about what could be expected from forced convective heat transfer alone. However, the analysis is much more complicated than that. It is likely that turbulent flow may exist over the module with a wind speed exponent of 0.8 (3). The S shape of the curves may be due to a change from laminar to turbulent flow. Data taken by Stultz and Wen (1) showed convection heat transfer to be directly proportional to wind speed below 2 m/s. However, radiative heat transfer is the predominant mode at temperatures near NOCT (1). This would tend to reduce the slopes.

Three sets of duplicate tests were run on separate days at the same nominal conditions of ambient temperature, wind speed and direction to check repeatability. Results are shown in Table 1 and Figs. 6, 7, and 8. Two doublet and one triplet points are shown. Without any particular effort at precise matching of conditions, the ΔT_{ca} repeated within ±0.5°C in the worst case.

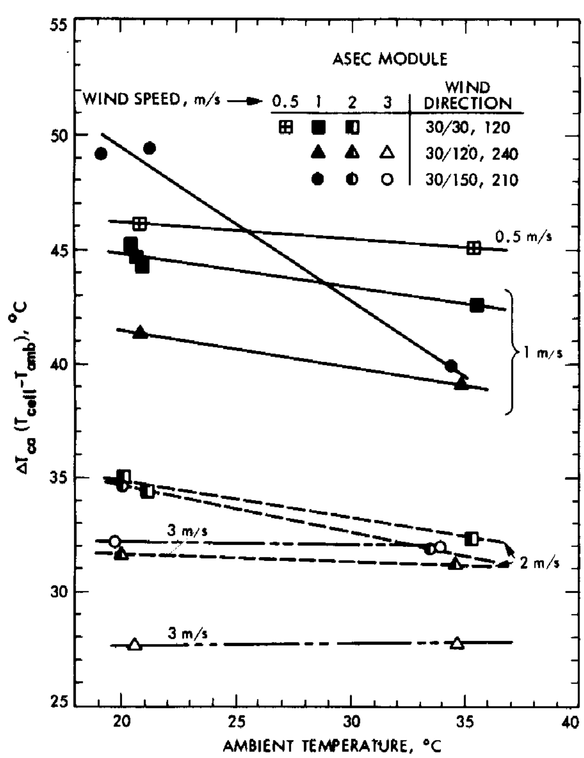

Fig. 8. Effect of ambient temperature on cell temperature rise

Examination of Table 1 shows that rather wide variations in the two cell temperatures can occur. Cell 1 minus Cell 2 values vary as much as $^{+5.2}_{-4.2}$°C. One of these is an anomalous high temperature mentioned above. All are probably the result of local reduced cooling due to eddies or shielding from the wind. Although this is less likely to happen outdoors, more than two cell temperatures should be measured to reduce errors in NOCT values.

The ΔT_{ca} measured at 1.0 m/s wind speed in natural sunlight at the JPL rooftop NOCT facility for this module is 34.5°C, as shown by the dashed line in Fig. 7. Depending on the wind direction, this ΔT_{ca} would require a controlled wind speed during the present test from 1.8 to 2.5 m/s.

Figure 8 and Table 2 show the effect of ambient temperature on the ΔT_{ca}. The anomalous high temperatures for the 30/150,210, 1 m/s condition can be seen again in the steep slope near the top of Fig. 8. Ignoring this curve, a rise in ambient temperature changes the ΔT_{ca} from +0.01 to -0.16°C per degree change in ambient temperature, depending on wind speed and direction. The mean value of the correction is -0.067°C/°C. This ambient temperature correction is less than that proposed in Refs. 1 and 2, which cover a range of -0.10 to -0.16°C/°C.

References 2, 4, and 5 reported consistent NOCT results with the same modules tested at different sites and by different investigators. NOCT values reported were at lower levels than in this present work. The investigators used Ref. 2, which requires a data averaging technique. The required conditions of winds between 0.25 and 1.75 m/s only, no east or west winds, and no gusts within 5 minutes of the data point are hard to achieve in practice. Unless very sophisticated wind instrumentation is used, many of the undesired conditions will creep in. Except for the rare wind condition below 1 m/s, these unwanted conditions cool the module efficiently. Averaging then gives low NOCT values and perhaps consistently low values for different investigators.

Table 3 summarizes data of the four modules tested both in this experiment and outdoors. Also shown are data on two other types of modules mounted at the JPL Field Test Site, an Arco Block III and a Motorola Block III.

There are several problems with the data from the outdoor tests. Wind problems affect results at the NOCT rooftop facility but do not seem to be much of a problem at the JPL Field Test Facility, where the modules are shielded by upwind arrays (6). The sensor used at the JPL NOCT Facility, an Eppley Model 8-48, may be unstable. The calibration of this instrument is reported to change with tilt angle (7). It could change as much as 14% when tilted to 70° from horizontal. The change is in a direction to increase NOCT at low sun angles. The sensitivity factor of this instrument changed over 3% between an April 1979 and a December 1980 calibration at JPL.

The field test modules had thermocouples attached to the backing material. The cell temperatures shown include the ΔT between the backing and the cell estimated from measurements on a similar type of Motorola module and a not-so-similar ARCO Block IV module (5.5 and 3.0°C, respectively).

Table 3 shows that the NOCT data from the outdoor JPL rooftop facility are about 10°C lower than the average of the chamber measurements at 1 m/s, 30° tilt. However, these outdoor NOCT values appear reasonable when one considers the problems of generally stronger winds than 1 m/s and low correction factors, the superior cooling of gusts and east or west (±30°) winds and the long thermal time constants of the modules.

Table 3 shows that the space chamber and the field test NOCT values are close. If a small downward correction for radiation error is applied to the chamber data, the match would be better yet. The four modules that have been tested in the chamber should be mounted at the Field Site and data compared.

Table 2. Effect of ambient temperature on cell temperature rise

Tilt/Wind Direction	Wind Speed, m/s	Temperatures, °C		Temperatures, °C		$\frac{\Delta(\Delta T_{ca})}{\Delta T_{amb}}$
		Ambient	ΔT_{ca}	Ambient	ΔT_{ca}	
30/30,330	0.5	20.9	46.1	35.4	45.1	-0.069
	1.0	21.0	44.2	35.5	42.6	-0.110
	2.0	20.1	34.0	35.3	32.3	-0.112
30/120,240	1.0	20.8	41.3	34.8	39.1	-0.157
	2.0	20.0	31.6	34.6	31.2	-0.027
	3.0	20.5	27.7	34.6	27.8	+0.007
30/150,210	1.0	19.2	49.1	34.4	39.9	-0.605
	2.0	20.1	34.9	33.3	34.5	-0.030
	3.0	19.7	32.4	33.5	31.9	-0.036

Table 3. Outdoor NOCTs vs cell temperatures from controlled tests

Module	Outdoor NOCT Measurement, °C	Controlled Test in Space Simulator: Wind Speed, m/s	Tilt/Wind Direction, Cell Temp, °C			
ASEC 001 Model 60-3044F	54.5		0/0	58.4	30/0,360	66.1
			0/90,270	62.2	30/30,330	64.2, 64.6, 65.2
			15/120,240	62.7	30/60,300	63.5
			30/120,240	61.3	30/90,270	61.7
			45/120,240	62.4	30/120,240	61.3
					30/150,210	69.1, 69.4
					30/180	68.6
		2.0	30/0,360	53.4	30/90,270	52.3
			30/30,330	54.0, 54.4	30/120,240	51.6
			30/60,300	57.6	30/150,210	54.9
		3.0	30/120,240	47.7	30/150,210	52.4
Motorola 1302 Model MSP43C40	56.0	2.5	30/120,240	54.7		
		3.0	30/120,240	53.0		
Solarex 100392 Model 580-BT-R	56.0	3.0	30/120,240	50.0		
Spire 004 Model 058-000/B	56.0	2.5	30/120,240	53.9		
		3.0	30/120,240	53.0		

Module	Construction	JPL Field Test Site: Wind Speed, m/s	Wind Direction	Cell Temperature, Normalized to 100 mW/cm^2, °C
Motorola Block III MSP 21D10	Glass superstrate, stainless substrate	0 to 1.5	South to southwest	61.5
ARCO-Solar Block III ICD 10699C	Glass superstrate, laminate, airspace, alum pan	0 to 1.5	South to southwest	60.5

From the foregoing, it appears that the best site for NOCT measurement is in the middle of a field of modules, such as at the JPL Field Test Site. The winds there, as measured atop a 6-m mast, were much lower than on the JPL NOCT rooftop facility located nearby. Furthermore, the local wind at a module in the field array is much less than on the 6-m mast (6). Data are much more stable at the JPL Field Test Site than on the roof.

The use of the space chamber at JPL should be feasible. However, further development work would be needed to establish a "sky" radiation correction factor and to define wind speed and direction without "hot spots" so as to simulate typical field conditions. A deterministic chamber test is very desirable that would require no wind or ambient temperature corrections and would permit measurement of NOCT for several modules in half a day. The "sun" would always be available.

Figures 9 and 10 give some approximate wind and ambient temperature correction factors for the ASEC module for two different wind directions based on limited data. The wind correction factors given here are much larger than those given in Refs. 1 and 2.

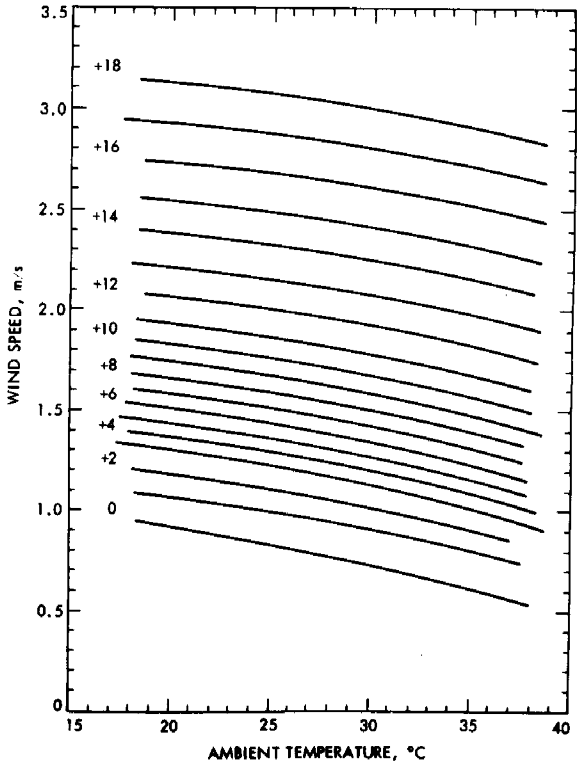

Fig. 9. NOCT correction factor, °C, for module position 30/30,330

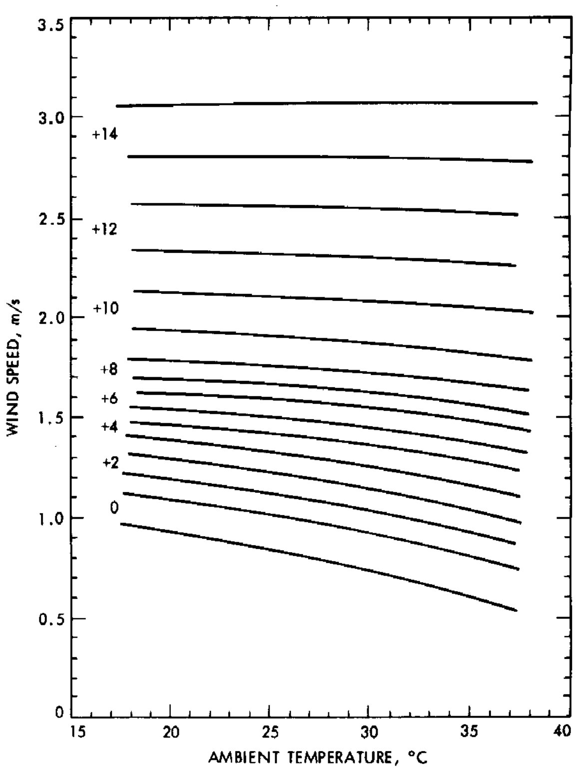

Fig. 10. NOCT correction factor, °C, for module position 30/120,240

Although most of the data presented are for one module type, it is likely that the conclusions apply to many others, especially for those with a glass front, polymer back and a metal frame.

Recommendations for further work in this area include the following:

(1) Investigate more fully the data from various field application sites. Modules in the interior of even modest-sized installations are well protected from wind, except perhaps direct east or west winds. Test the four modules used in this work at the JPL Field Test Site.

(2) Install a wind fence around the rooftop NOCT test facility to more closely simulate conditions of the interior of a module field. Determine NOCT values and compare with previous values measured there and at field sites.

(3) Develop radiative heat transfer correction factors for space chamber measurements of NOCT, if necessary. Run further tests to develop procedures for chamber measurement of NOCT. Investigate the hypothesis that hot spots may develop from stable air flow.

At that point it would be desirable to review NOCT measurement procedures to see if an alternate is needed to the methods described in Refs. 1 and 2.

CONCLUSION

These controlled tests show that wind has a very strong effect on the cell NOCT and a large correction factor must be used for off-nominal conditions. The strong cooling from gusts and winds of over 1 m/s in the natural environment has an effect which lasts for 20 to 30 minutes. Also, it is probable that near-east or near-west winds which result in lower cell temperatures do occur frequently in the field. These factors make it difficult to arrive at a correct NOCT. Most of the effects described result in lower apparent NOCT readings. NOCT measurements by standard procedures at JPL are lower than for these controlled environment tests and limited field test results. Tests by module manufacturers have generally given even lower values.

Further development work on NOCT measurements is needed. More testing in the space chamber would increase the understanding of wind cooling of modules. A new controlled environment NOCT procedure in the space chamber is feasible but would require further development. Use of a field test site for NOCT measurements is very promising. A wind fence surrounding the JPL rooftop NOCT facility should be tried. NOCT measurement procedures should be reviewed and perhaps an alternate to the methods presently used should be developed.

ACKNOWLEDGMENT

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